RESEARCH MEMORANDUM

EFFECT OF INLET AIR DISTORTION ON THE STEADY-STATE AND SURGE CHARACTERISTICS OF AN AXIAL-FLOW TURBOJET COMPRESSOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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EFFECT OF INLET AIR DISTORTION ON THE STEADY-STATE AND SURGE CHARACTERISTICS OF AN AXIAL-FLOW TURBOJET COMPRESSOR

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SUMMARY

An investigation was conducted in an altitude test chamber to determine the effects of inlet airflow distortion on the compressor steady-state and surge characteristics of a high-pressure ratio, axial-flow turbojet engine. Circumferential-type inlet flow distortions were investigated, which covered a range of distortion sector angles from 20° to 168°
CL-1 and distortion levels up to 22 percent.

The presence of inlet airflow distortions at the compressor face resulted in a substantial increase in the local pressure ratio in the distorted region, primarily for the inlet stages. The local pressure ratio in the distorted region for the inlet stages increased as either the distortion sector angle decreased or the percent distortion increased. The average compressor-surge pressure ratio was much more sensitive to inlet airflow distortions at lower engine speeds than at engine speeds near rated. Hence, compressor-surge margin reduction due to inlet airflow distortion was quite severe at the lower engine speeds. Although the average compressor-surge pressure ratio was generally reduced with inlet flow distortion, local pressure ratios across the distorted sector of the compressor were obtained during surge and were significantly greater than the normal compressor-surge pressure ratio. This was a result of increased loading of the inlet stages in the distorted region.

INTRODUCTION

Inlet airflow distortions are often encountered in high-performance aircraft as a result of flow separations or severe bends in inlet ducting, and from aircraft flight maneuvers where high yaw or pitch angles are encountered. An over-all program has been established at the Lewis laboratory to determine the effect of inlet flow distortions on the steady-state and transient characteristics of turbojet engines. Previous investigations on a number of turbojet engines indicate that inlet flow distortions can produce penalties in engine steady-state performance, reduce

compressor-surge limits, and cause excessive local turbine temperatures or combustor blowout. A number of investigations considering the effects of airflow distortions are presented in references 1 to 4.

As part of the over-all distortion program, an investigation was made in the altitude wind tunnel to determine the effects of inlet airflow distortion on the compressor steady-state and surge characteristics of a high-pressure-ratio, axial-flow turbojet compressor. Circumferential-type inlet flow distortions, which covered a range of distortion sizes (sector angles) from 20° to 168°, and a severity of distortion (percent distortion) 4641
up to 22 percent, were investigated. The distortions were introduced into the engine with a unique device with which both the distortion size and severity could be remotely controlled. The distorted-flow sector could also be rotated around the compressor face, and in this manner, the distortion flow path and variation in interstage local loading could be studied with a limited amount of interstage instrumentation. Data are presented for engine steady-state operation to show the distorted-sector flow path and washout and the effect of inlet airflow distortion on stage loading. Compressor over-all surge pressure ratio is presented for a range of distortion sizes and engine speeds at a simulated altitude of 35,000 feet and a 0.8 flight Mach number.

SYMBOLS

The following symbols are used in this report:

N engine speed, rpm

P total pressure, lb/sq ft abs

θ ratio of inlet temperature to NACA standard temperature

Subscripts:

av average

d distorted region

u undistorted region

1 compressor inlet

8 compressor outlet

Parameters:

$\frac{P_u - P_d}{P_u}$ distortion severity (or level) at the compressor inlet

$\frac{\Delta P_8/P_1}{P_8/P_1}$ compressor surge margin - for a given engine speed the average surge pressure ratio minus the average steady-state pressure ratio divided by the average steady-state pressure ratio

APPARATUS

Engine and Installation

The engine was installed in the altitude wind tunnel as shown in figure 1. Engine-inlet conditions were obtained with the use of the tunnel refrigerated-air and exhaust facilities.

A sketch indicating the general outline of the engine with a cross section of the compressor is shown in figure 2. The primary components of the engine are a 15-stage, variable-inlet-guide-vane compressor, a can-annular combustor, and a two-stage turbine.

Distortion Device

The distortion device was designed to provide independent control of both distortion size (sector angle) and severity of distortion (percent distortion). The distortions were obtained (at the face of the compressor) by bleeding inlet airflow from an isolated section of the compressor annulus. A cross-sectional view of the distortion device is shown in figure 2. The distorted section of the compressor annulus was separated from the undistorted section by two splitter plates that extended from a choked screen several feet upstream of the compressor face to within 5 inches of the inlet guide vanes. The splitter plates were mounted on concentric rotatable drums, which could be rotated independently to vary the distortion sector angle or could be rotated with a fixed sector angle to vary the position of the distortion at the compressor face. By varying the amount of airflow bleed that is off the distorted sector, the percent distortion could be varied independently of engine speed or distortion sector angle. The bleedflow from the distorted sector was controlled with a throttle valve in the overboard line.

INSTRUMENTATION

The location and amount of steady-state and transient instrumentation is shown in figure 2. Transient pressure and engine speed signals were fed into a multichannel photographically recording oscillograph. Transient pressures were measured with variable-reluctance-type pressure transducers. Response of the transient measuring system was flat up to a frequency of 30 to 40 cycles per second.

PROCEDURE

Compressor steady-state performance was obtained over a range of engine speeds with uniform inlet flow and for a range of distortion sector angles from 20° to 168° and percent distortion from 8 to 22 percent. To determine the distortion flow path during steady-state engine operation, a distortion was introduced at the compressor face with the distortion device and rotated slowly around the compressor annulus past axially alined interstage instrumentation. As the distortion swept past the instrumentation, a photographic record of the circumferential pressure variation due to the distortion was obtained at several stations in the compressor using the transient-pressure recording system. The photographic traces were then converted into pressures, and circumferential profiles at several points in the compressor were plotted. Analysis of the interstage pressure profiles was then made to determine distortion-flow spreading and stage-group pressure-ratio variation caused by the distortion. In order to determine stage-group local pressure ratios, the streamline flow path through the compressor had to be known. This was determined by injecting freon gas at the compressor inlet and observing the flow path through the compressor with a freon-gas detector. The streamline rotation observed in this manner agreed fairly well with the streamline rotation indicated by the total-pressure contours.

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Compressor surge limits were obtained over the same range of distortions investigated during the steady-state engine operation. Compressor surge was obtained by introducing step increases in fuel flow into the engine combustor. Surge limits were obtained over an engine speed range from just above the compressor rotating stall speed to rated engine speed. All data were obtained at a simulated flight altitude of 35,000 feet and 0.8 flight Mach number with inlet guide vanes open.

RESULTS AND DISCUSSION

Definition of Inlet Flow Distortions

Typical static- and total-pressure profiles at the face of the compressor are shown in figure 3 for several representative distortions. The total-pressure measurement was made just downstream of the leading edge of the inlet guide vanes, and static pressure was measured just ahead of the inlet guide vanes (fig. 2). No significant radial pressure gradient exits at the compressor face for any of the distortions; for this reason, pressure profiles only at midspan are presented in figure 3.

Compressor-inlet pressure profiles are shown for sector angles of 20°, 70°, and 168° in figure 3(a) and for 8- , 15- , and 22-percent distortion in figure 3(b). The distortion sector angle was considered as the angle between the distortion splitter plates, while the percent

distortion is defined as the ratio of the difference between the undistorted pressure and the pressure in the distorted region to the undistorted pressure (P_u-P_d/P_u). Inspection of the total-pressure profiles indicates very little mixing between the high pressure (undistorted airflow) and the low pressure (distorted airflow) in the 5-inch axial distance between the end of the splitter plates and the inlet guide vanes. However, the more gradual slopes to the static-pressure profiles indicate an inwash flow or nonaxial flow immediately ahead of the inlet guide vanes. The static- and total-pressure profiles indicate that generally at the
4641 inlet guide vanes a lower axial velocity exists in the distorted region than in the region outside the distortion.

Effect of Flow Distortion on Steady-State Compressor Operation

Compressor internal flow patterns with inlet airflow distortions present at the face of the compressor were studied by moving the distortion around the compressor annulus and recording the total-pressure variations at several fixed stations in the compressor. The result of one of these surveys is shown in figure 4. Total-pressure defect contours are shown from the compressor inlet to nearly the compressor outlet for a corrected engine speed of 7800 rpm, a 15-percent distortion, and 70° sector angle in figure 4(a). The total-pressure defect contours show that the distorted flow gradually affects a larger portion of the compressor annulus as it proceeds to the rear of the compressor. The 70° sector angle of the distortion, which existed at the compressor face, has spread to approximately 265° at the inlet to the 14th-stage rotor. Also apparent from the contours is the rotation of the flow streamlines. By considering the low-pressure region or valley of the contours, a streamline rotation of approximately 100° (which agrees fairly well with freon trace data) in the direction of compressor rotation is noted from compressor inlet to outlet. The maximum total-pressure difference does not vary significantly from compressor inlet to outlet, even though the compressor total-pressure level increases, indicating that stage total-pressure defect on a percentage basis decreases from compressor inlet to outlet. Total-pressure defect contours presented as a percent of stage undistorted pressure are shown in figure 4(b). The percentage variation in total pressure diminishes from 15 percent at the compressor inlet to about 2 percent at the compressor outlet. Total-pressure contours are not shown after the 14th rotor inlet, because the variation in total pressure encountered because of the distortion was approaching the transient instrumentation accuracy. Examination of the total-pressure contours obtained with other distortion sector angles and percent distortions revealed the same general trends as those shown in figure 4.

Since the compressor-outlet, circumferential total-pressure distribution was approximately constant for the distortions investigated, the airflow in the distorted region is compressed to a higher pressure ratio

than airflow outside the distorted region. This is illustrated in figure 5 where compressor pressure ratio in the distorted region $(P_8/P_{1,d})$ and the average compressor pressure ratio $(P_8/p_{1,av})$ for several distortion sector angles and magnitudes are compared with the normal compressor pressure ratio. For the range of distortion sector angles and percent distortion investigated the pressure ratio across the distorted region was substantially higher than the normal pressure ratio (as much as 21 percent above normal), while the average compressor pressure ratio was slightly lower than the normal pressure ratio. Although increasing the 4641 percent distortion raised the pressure ratio across a distorted region of given size, an opposite trend is noted for increasing the sector angle with a given percent distortion.

A study of compressor interstage pressure ratios indicated that most of the increase in pressure ratio across the distorted section of the compressor was a result of increased pressure ratio (loading) in the inlet stages. An example of the variation in interstage pressure ratio in the sector of the compressor annulus affected by the distortion is shown in figure 6 for a 70° sector angle, 15-percent distortion, and a corrected engine speed of 7800 rpm. The stage-group pressure ratios presented are those obtained across a streamline flow path (see PROCEDURE) at midspan. A sharp increase in local pressure ratio above the normal stage-group pressure ratio is noted in the distorted region (fig. 6) for the inlet-stage group (stages 1 to 4) as compared with the middle- and outlet-stage groups. This increase in inlet-stage-group pressure ratio is probably a result of the lower axial velocities existing in the distorted region ahead of the inlet guide vanes, which increases the rotor angle of attack of the inlet stages. Stage-group pressure ratio outside the distorted region is generally lower than the normal-stage group pressure ratio except for the outlet-stage group (stages 11 to 15).

The inlet-stage-group local pressure ratio dips abruptly below the undistorted-region pressure ratio as the rotor approaches the distorted region while as the rotor passes out of the distorted region, the local pressure ratio remains above the undistorted-region pressure ratio for some distance. A possible explanation for this trend lies in the fact that at the compressor-inlet guide vanes and possibly in the first few stages there is an inwash flow component due to the static-pressure gradient between the distorted and undistorted regions, which is in the direction of compressor rotation as the rotor approaches the distorted region and opposite to rotation as the rotor leaves the distorted region. The inwash flow component would thus result in a local decrease in the rotor angle of attack (decrease in pressure ratio) as the rotor moves into the distorted sector and would correspondingly maintain a relatively higher rotor angle of attack (higher pressure ratio) as the rotor moves out of the distorted sector. The peak inlet-stage-group pressure ratio occurs just before the rotor leaves the distorted sector, because at this point the increase in local-stage-group pressure ratio due to the distortion is augmented by the increase in stage-group pressure ratio due to inwash flow.

The effect of distortion sector angle and percent distortion on the average-stage-group pressure ratio in the region affected by the distortion is shown in figure 7 for a corrected engine speed of 7800 rpm. The effect of both distortion sector angle and percent distortion is most pronounced on the inlet-stage-group pressure ratio. The inlet-stage-group pressure ratio in the distorted region is markedly increased as the distortion sector angle is reduced or the percent distortion increased.

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Effect of Inlet Flow Distortion on Compressor-Surge Limits

<u>Effect of sector angle</u>. - The effect of distortion sector angle on compressor over-all surge pressure ratio is shown in figure 8 for a range of engine speeds. The average compressor-surge pressure ratio (fig. 8(a)) is defined as the ratio of average values of compressor-inlet and outlet pressure at surge. Peak surge pressure ratio or average surge pressure ratio across the distorted sector of the compressor (fig. 8(b)) is defined as the ratio of the average compressor-outlet pressure to the inlet pressure in the distorted region at surge $(P_8/P_{1,d})$. Increasing the distortion sector angle, within the range investigated, resulted in a reduction in both average and peak surge pressure ratios. The average surge pressure ratio was generally lower than the normal surge pressure ratio. The peak surge pressure ratio was higher than the normal surge pressure ratio at high engine speeds, but for large sector angles, the peak surge pressure ratio fell below the normal surge pressure ratio at low engine speeds.

A crossplot of compressor peak and average surge pressure ratios, showing directly the effect of sector angle, is shown in figure 9 for corrected engine speeds of 7600 and 6600 rpm. Compressor average surge pressure ratio is noticeably more sensitive to increasing sector angle at low engine speed (6600 rpm) than at high engine speed (7600 rpm). A maximum reduction of 17 percent in average surge pressure ratio below the normal surge pressure ratio is observed at the low engine speed for sector angles between 80° and 168°. Compressor peak surge pressure ratios considerably greater than the normal surge pressure ratio are observed (fig. 9) for small sector angles and high engine speed. A compressor peak surge pressure ratio 19 percent above the normal surge pressure ratio is noted for a 20° sector angle at the high speed. However, at the low engine speed, the peak surge pressure ratio was lower than the normal surge pressure ratio at sector angles greater than 50°.

Existence of compressor peak surge pressure ratios (maximum local pressure ratio developed by the distorted segment of the compressor) above the normal surge pressure ratio results from changes in compressor steady-state loading distribution among the stages brought about by the compressor-inlet flow distortion. It was shown earlier in this report that for high corrected engine speeds the presence of inlet flow distortion resulted in

a substantial increase in pressure ratio of the inlet stages in the distorted region, while the middle and outlet stages were not significantly affected. At high engine speeds (near rated), the rear compressor stages are highly loaded and are the critical stages at surge. Because the inlet distortion does not materially affect the local operating pressure ratio of these stages, the peak surge pressure ratio then is higher than the normal surge pressure ratio because of the increase in the operating pressure ratio of the inlet stages. However, as engine speed is reduced, the inlet stages become more critical at surge. Consequently, increases in inlet-stage loading due to the distortion would then diminish the peak surge pressure ratio at low speeds below the normal surge pressure ratio. The observed reductions in peak surge pressure ratio (for sector angles above 50°) at low speeds was also believed to be influenced by a locally stalled section of the compressor that existed at low speeds. An example of the stalled region obtained during steady-state engine operation with the 70° sector angle and 15-percent distortion is shown in figure 10. The total-pressure contours show a locally stalled region at the hub, which is initiated in the first stage at an angular position of approximately 140°. The stalled region persisted to as far back as the eighth stage of the compressor.

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The effect of distortion sector angle on compressor surge margin (which represents the rate at which engine speed can be accelerated) is shown in figure 11 for the engine-speed range investigated. The compressor surge margin is defined as the ratio of the difference between the average surge pressure ratio and the average steady-state pressure ratio to the average steady-state pressure ratio. The largest reduction in surge margin occurred at the low engine speeds. The surge margin was reduced by 25 to 65 percent at a corrected engine speed of 6600 rpm for the range of distortion sector angles presented. At a corrected engine speed of 7600 rpm, there is a general reduction in surge margin with increasing distortion sector angle, however, the reductions are moderate compared with those at the low speed.

Effect of percent distortion. - The effect of percent distortion on compressor average and peak surge pressure ratio is presented in figure 12 for the engine-speed range investigated. The average compressor pressure ratio was generally lower than the normal surge pressure ratio, while peak surge pressure ratios much higher than the normal surge pressure ratio were again obtained at high engine speeds.

A crossplot showing the effect of percent distortion on both average and peak surge pressure ratios for a high and low engine speed is shown in figure 13. At the high speed, the average surge pressure ratio is reduced approximately 8 percent below the normal surge pressure ratio as the percent distortion was increased from 0 to 22 percent. At the same time the peak surge pressure ratio increased by 15 percent. At the low engine speed the average surge pressure ratio was reduced a maximum of 17 percent for a 15-percent distortion.

The effect of percent distortion on the compressor surge margin is shown in figure 14. There is a severe penalty in surge margin at low engine speeds with inlet flow distortion compared with the normal surge margin. At high engine speeds there is a general reduction in surge margin as the percent distortion is increased. However, for the smallest distortion, surge margins equal to or slightly greater than the normal surge margin were obtained.

SUMMARY OF RESULTS

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An investigation was conducted to determine the effect of inlet flow distortion on compressor steady-state and surge characteristics. The following results were obtained:

1. A study of the flow path of the distorted area indicated that the distorted region affected more of the compressor annulus, and the percentage variation in total pressure diminished as the distorted region passed through the compressor. At the compressor outlet the circumferential total-pressure distribution on a percentage basis was approximately constant for the range of distortions investigated. The presence of a distortion at the compressor face resulted in a substantial increase in the local pressure ratio in the distorted region primarily for the inlet stages. The pressure ratio in the distorted region for the inlet stages was found to increase as either the distortion sector angle decreased or the percent distortion increased.

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2. Increases in either the distortion sector angle or the percent distortion reduced the average compressor surge pressure ratio. Average compressor surge pressure ratio was more sensitive to inlet flow distortions at lower engine speeds than at engine speeds near rated. For a distortion sector angle of 168° and 15-percent distortion the average compressor surge pressure ratio was reduced by 19 percent at a corrected engine speed of 6600 rpm as compared with a 4-percent reduction at 7600 rpm. The compressor surge margin was also much more sensitive to inlet flow distortions at low engine speeds than at high engine speeds.

3. Although the average compressor surge pressure ratio was generally decreased with inlet flow distortions, the compressor was able to support local pressure ratios (peak surge pressure ratio) across the distorted region of the compressor that were higher than the normal surge pressure ratio, particularly at high engine speeds. Compressor peak surge pressure ratios as high as 19 percent above the normal surge pressure ratio were obtained. This was a result of an increase in the loading of the inlet

stages in the distorted region, which did not materially affect the average surge limits at high engine speed, but did lead to severe penalties in average surge limits at low engine speeds.

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National Advisory Committee for Aeronautics
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1. Wallner, Lewis E., Conrad, E. William, and Prince, William R.: Effect of Uneven Air-Flow Distribution to the Twin Inlets of an Axial-Flow Turbojet Engine. NACA RM E52K06, 1953.

2. Walker, Curtis L., Sivo, Joseph N., and Jansen, Emmert T.: Effect of Unequal Air-Flow Distribution from Twin Inlet Ducts on Performance of an Axial-Flow Turbojet Engine. NACA RM E54E13, 1954.

3. Harry, David P., III, and Lubick, Robert J.: Inlet-Air Distortion Effects on Stall, Surge, and Acceleration Margin of a Turbojet Engine Equipped with Variable Compressor Inlet Guide Vanes. NACA RM E54K26, 1955.

4. Fenn, David B., and Sivo, Joseph N.: Effect of Inlet Flow Distortion on Compressor Stall and Acceleration Characteristics of a J65-B-3 Turbojet Engine. NACA RM E55F20, 1955.

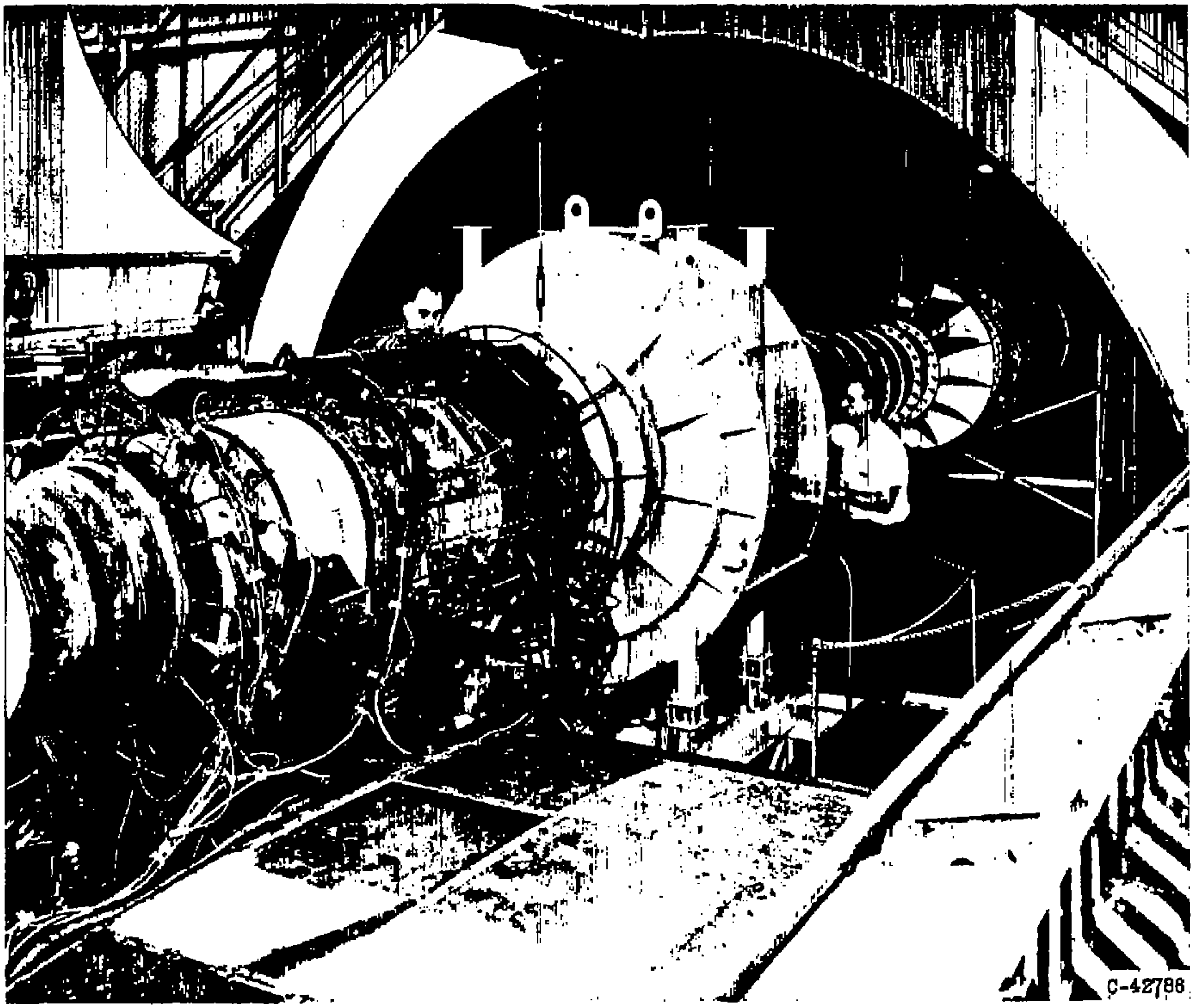
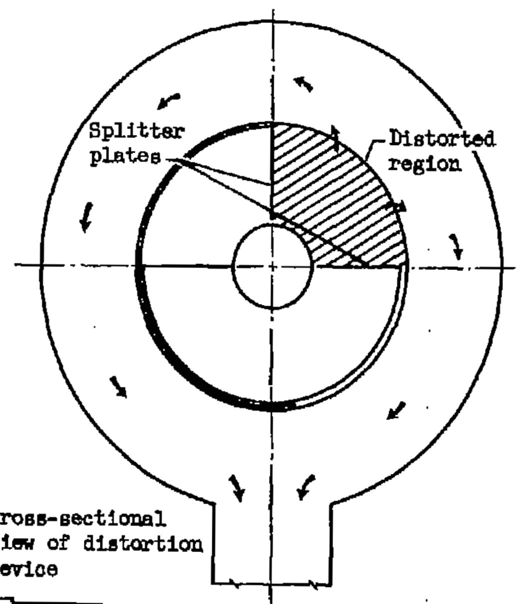


Figure 1. - Engine installed in altitude test chamber.

TABLE OF INSTRUMENTATION

Station	Location	Total-pressure measurements		Total-temperature measurements		Transient-pressure probes (a)
		Probes	Rakes	Probes	Rakes	
1	Compressor inlet	40	4	12	4	2
2	Inlet guide vanes	3	1	--	--	1
3	2nd stage inlet	10	2	--	--	1
4	5th stage inlet	5	1	--	--	2
5	8th stage inlet	5	1	--	--	2
6	12th stage inlet	5	1	--	--	1
7	14th stage inlet	5	1	--	--	1
8	Compressor outlet	20	4	24	4	2

a Midspan



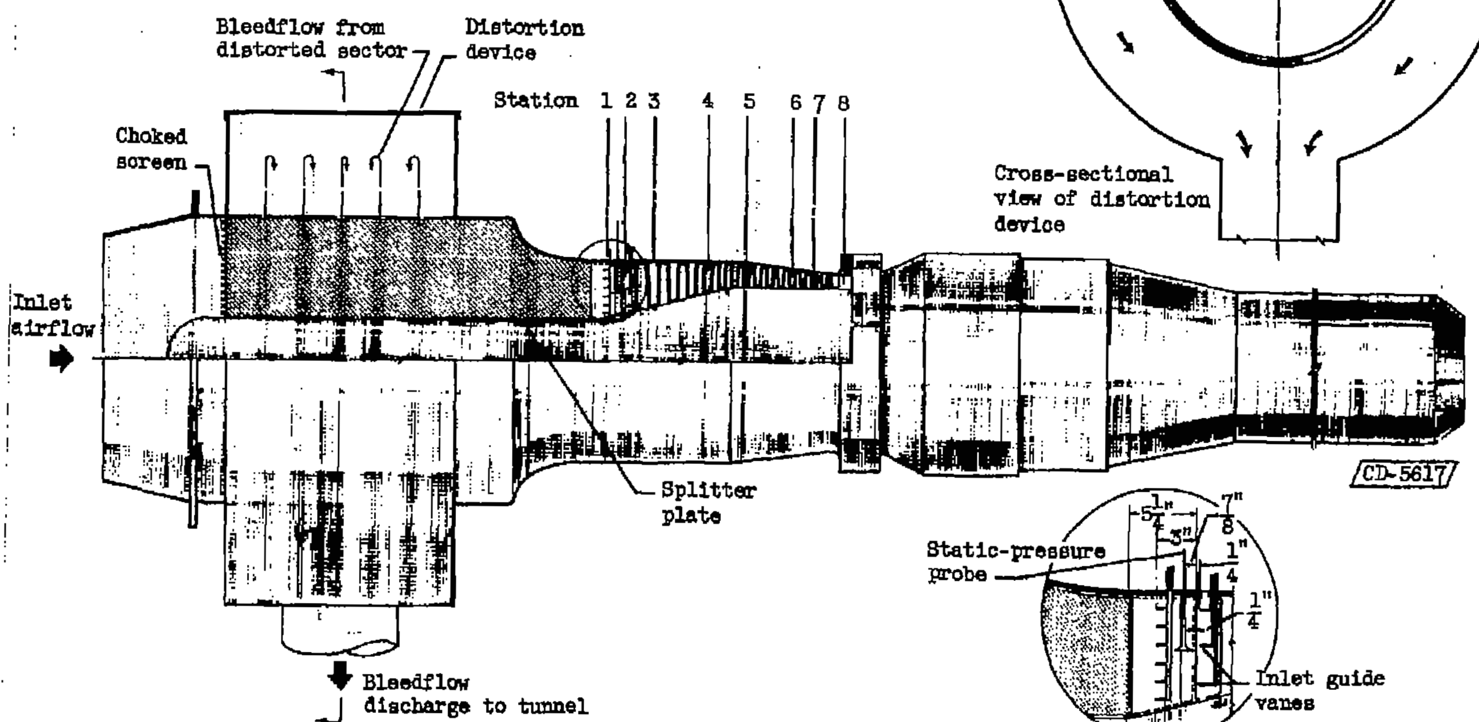


Figure 2. - Cross section of compressor showing instrumentation stations.

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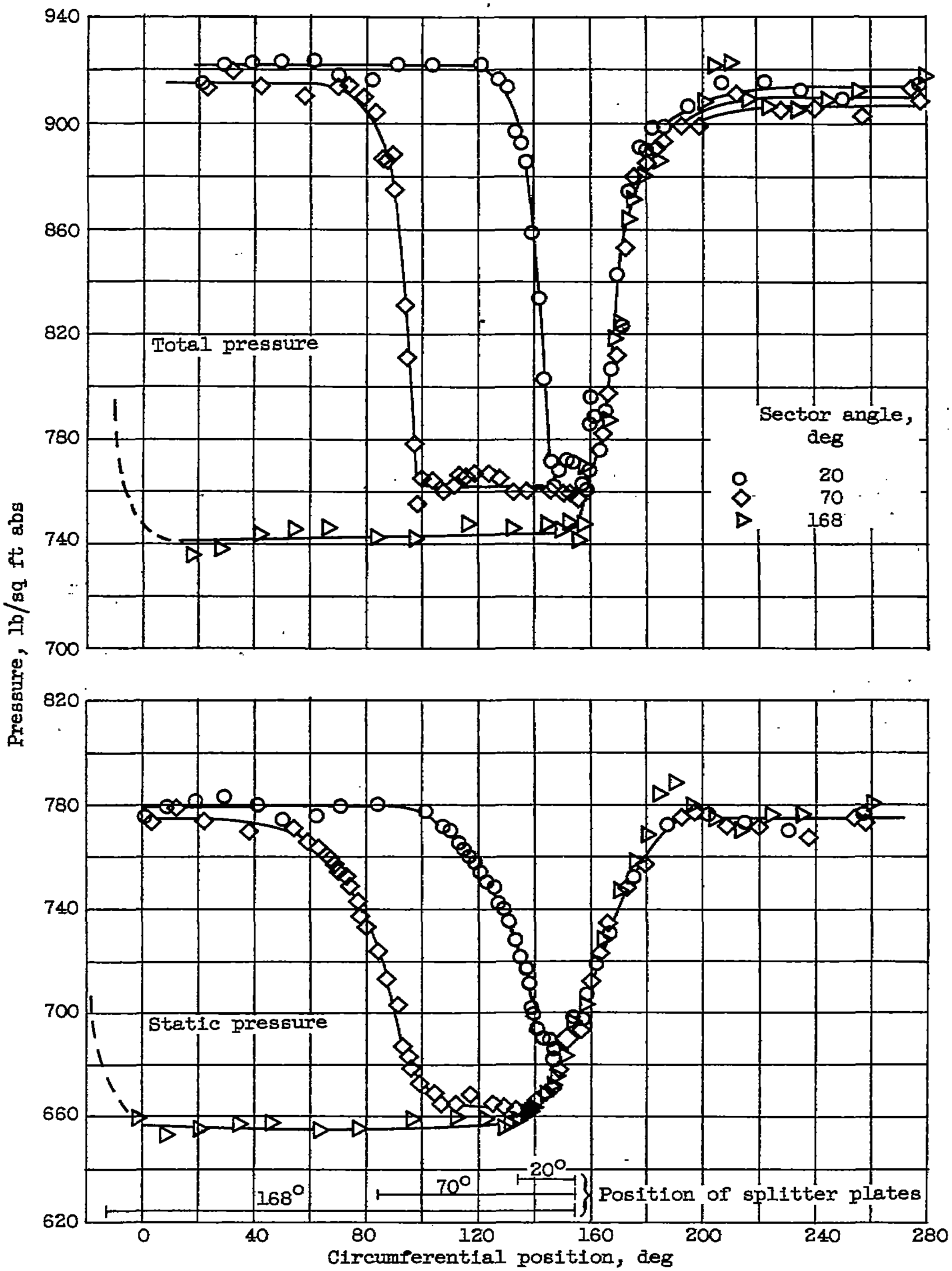

(a) Profiles for several sector angles; 15-percent distortion.

Figure 3. - Typical distortion profiles at compressor inlet.

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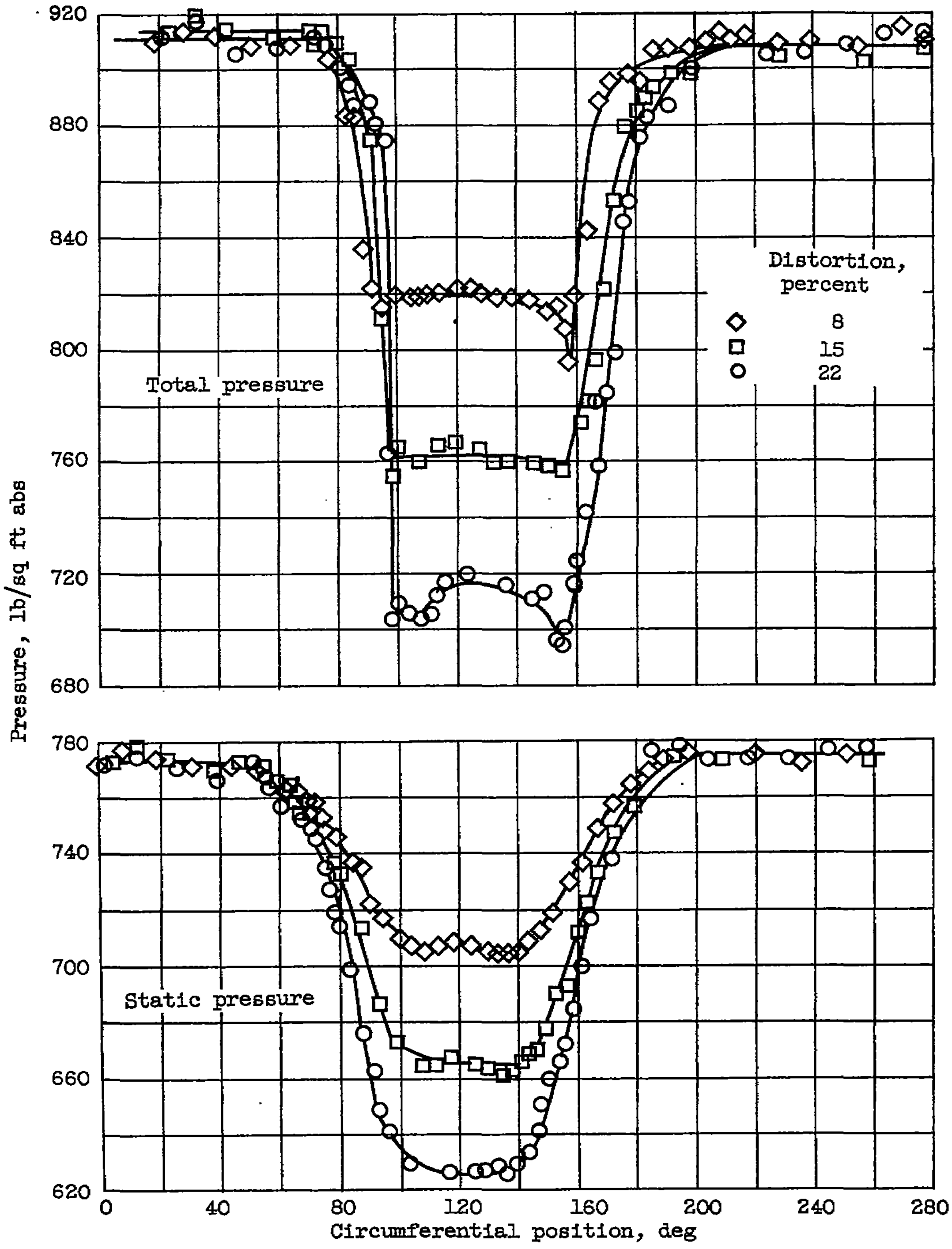

(b) Profiles for several percent distortions; 70° sector angle.

Figure 3. - Concluded. - Typical distortion profiles at compressor inlet.

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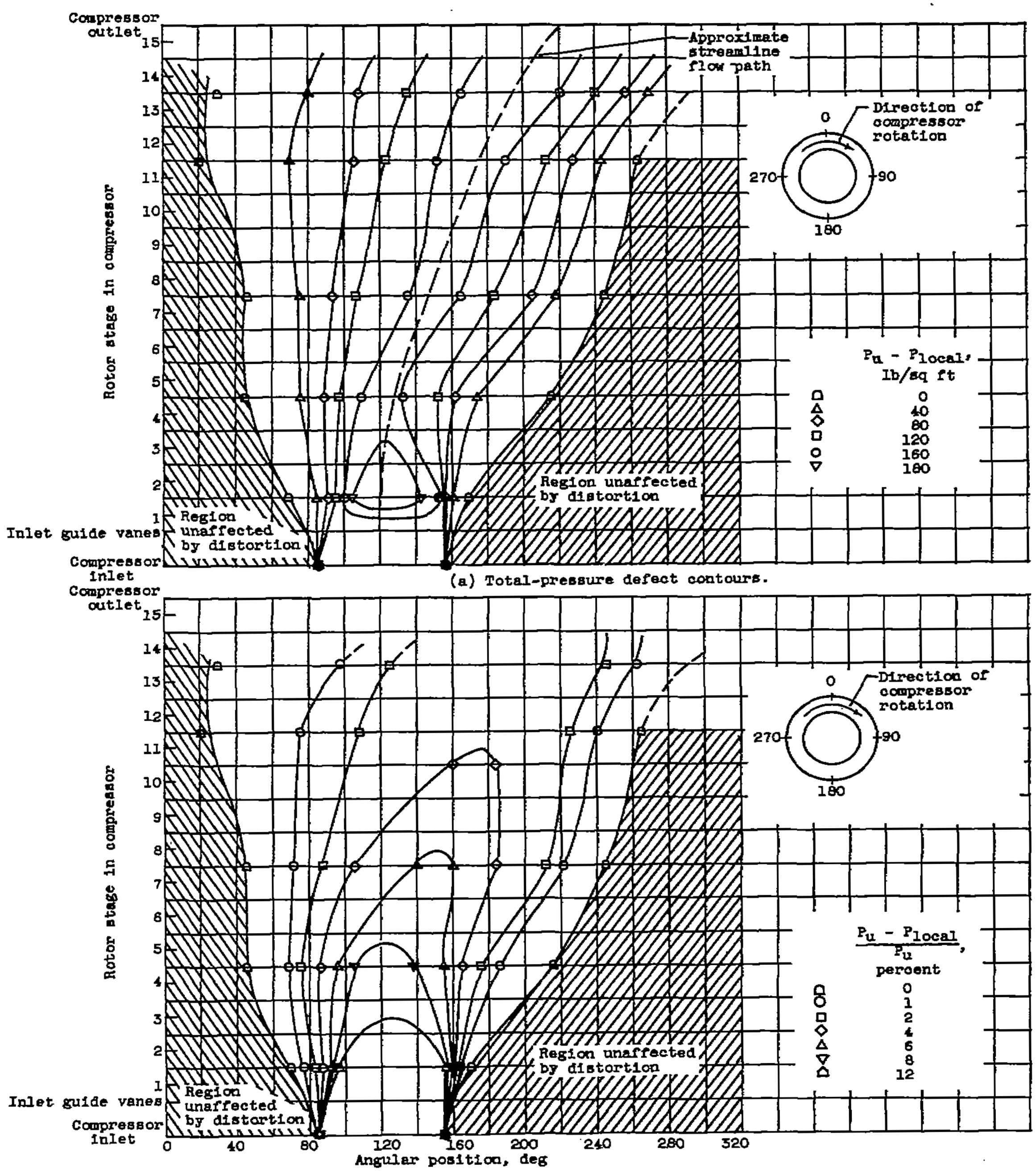

(b) Percent variation in total pressure.

Figure 4. - Distorted area flow contours; 15-percent distortion; 70° sector angle.

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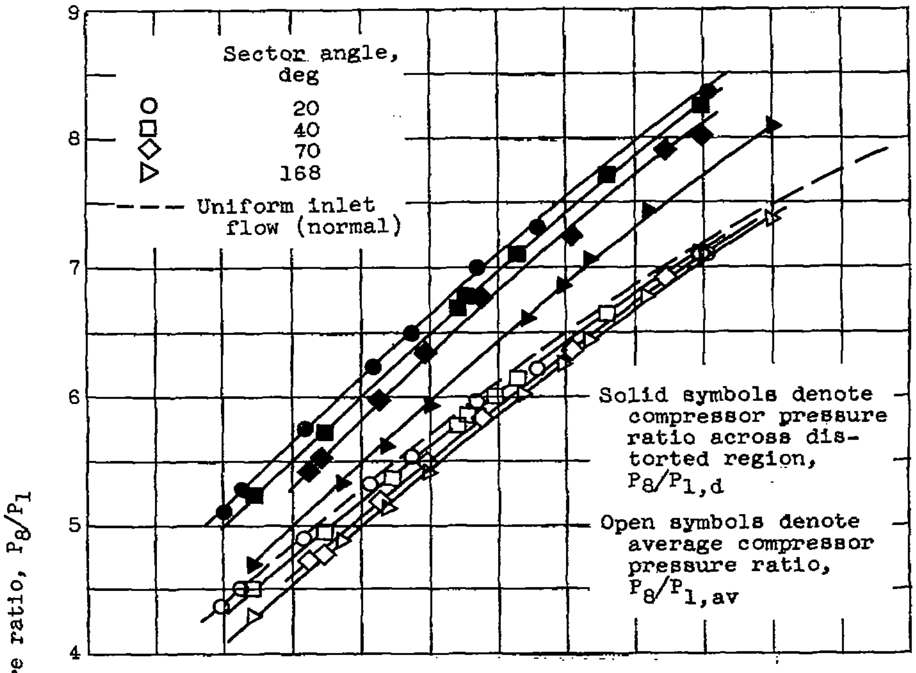
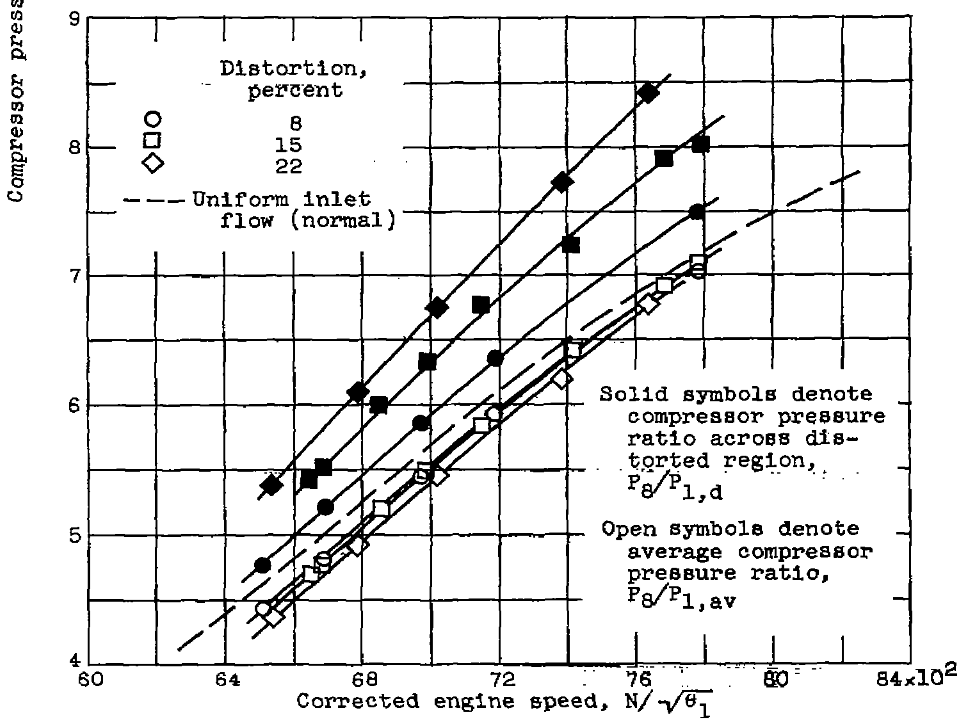


(a) Effect of distortion sector angle; 15-percent distortion.



(b) Effect of percent distortion; 70° sector angle.

Figure 5. - Effect of flow distortion on compressor peak and average steady-state operating pressure ratios.

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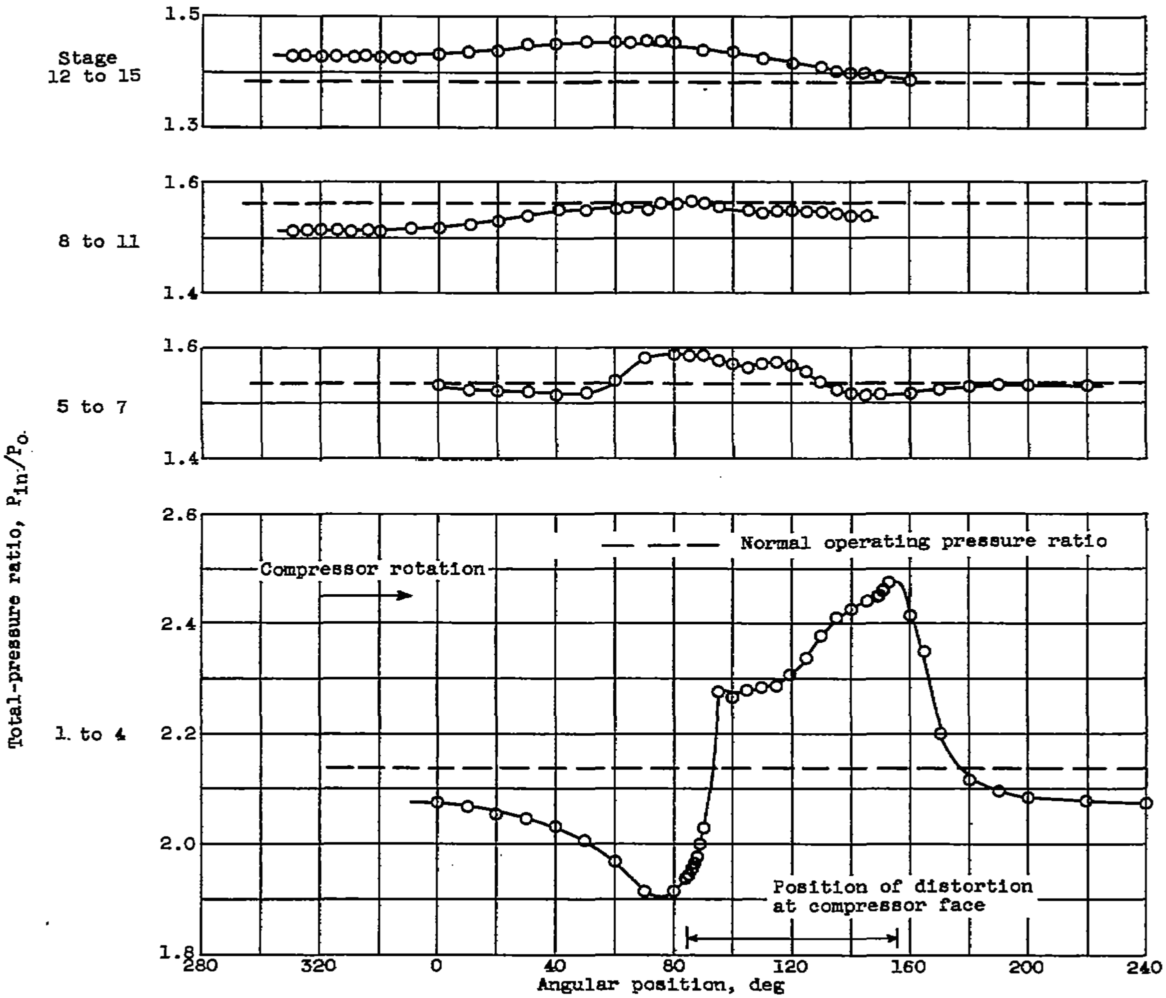

Figure 6. - Effect of inlet flow distortion on compressor interstage, local pressure ratios. Distortion, 15 percent; 70° sector angle.

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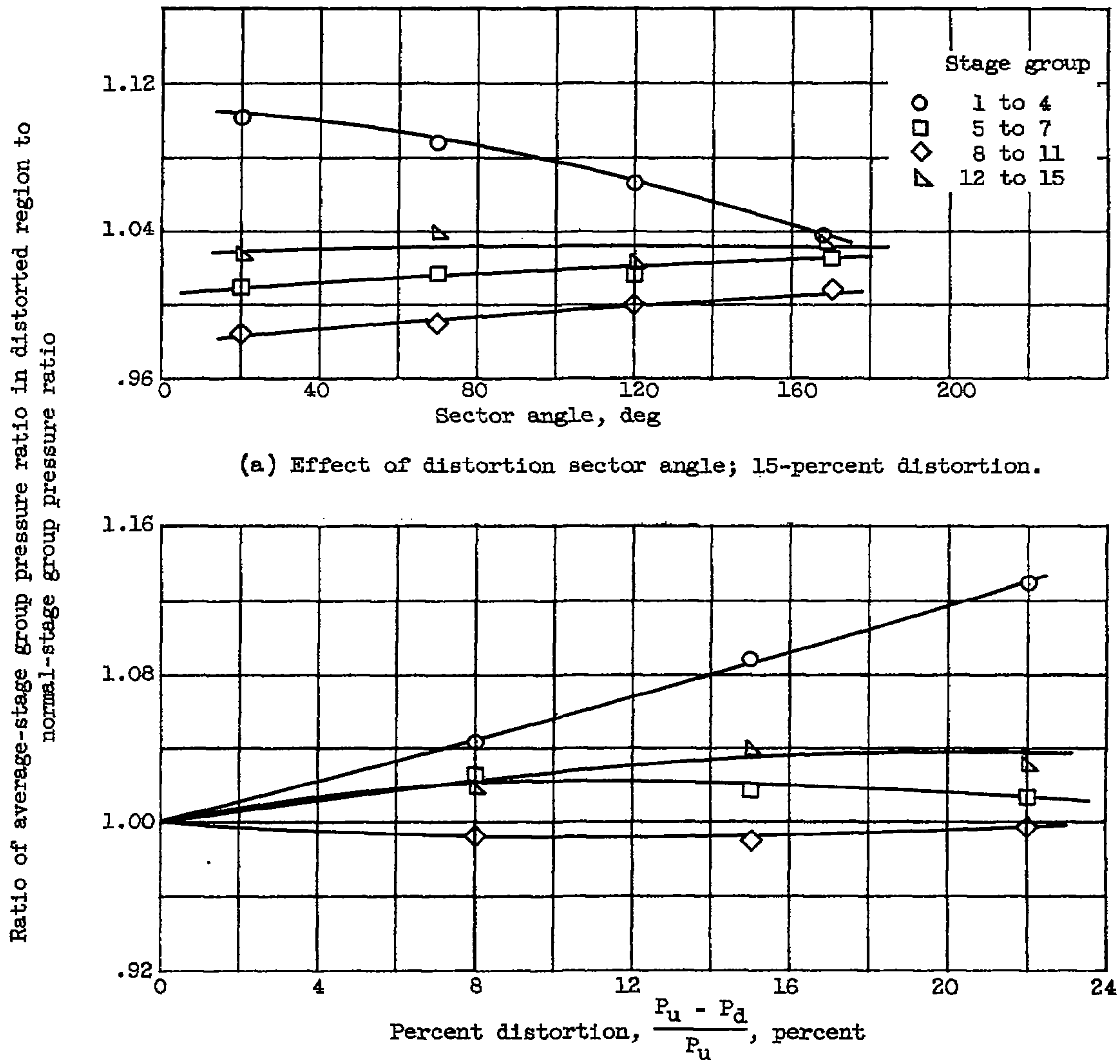

(a) Effect of distortion sector angle; 15-percent distortion.

(b) Effect of percent distortion; sector angle, 70°.

Figure 7. - Effect of inlet flow distortion on compressor-stage pressure ratio in the distorted region.

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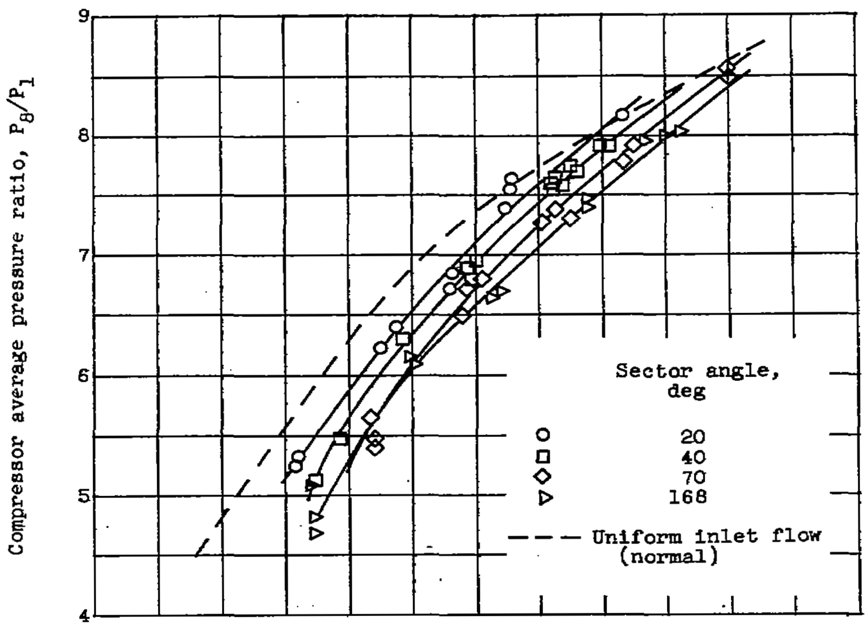
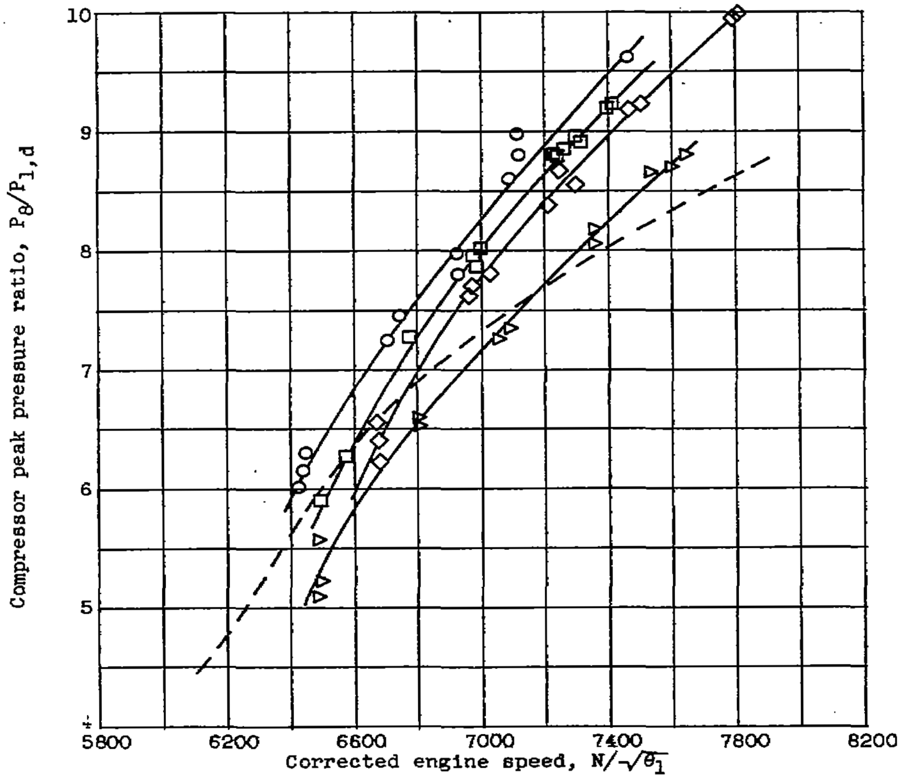


(a) Compressor average surge pressure ratio.



(b) Compressor peak surge pressure ratio.

Figure 8. - Comparison of compressor surge lines obtained with several distortion sector angles. Distortion, 15 percent.

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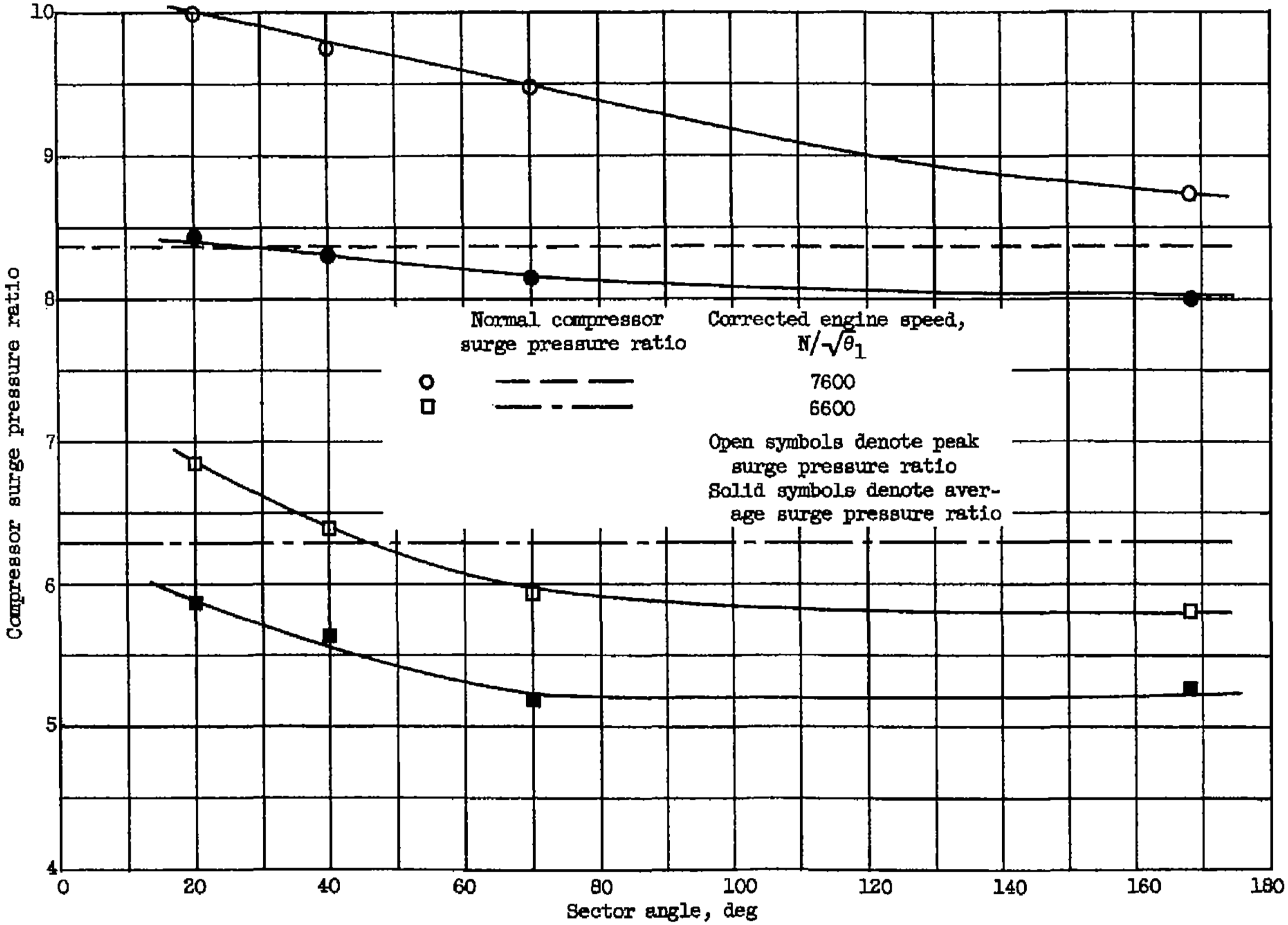

Figure 9. - Effect of distortion sector angle on compressor peak and average surge pressure ratio. Distortion, 15 percent.

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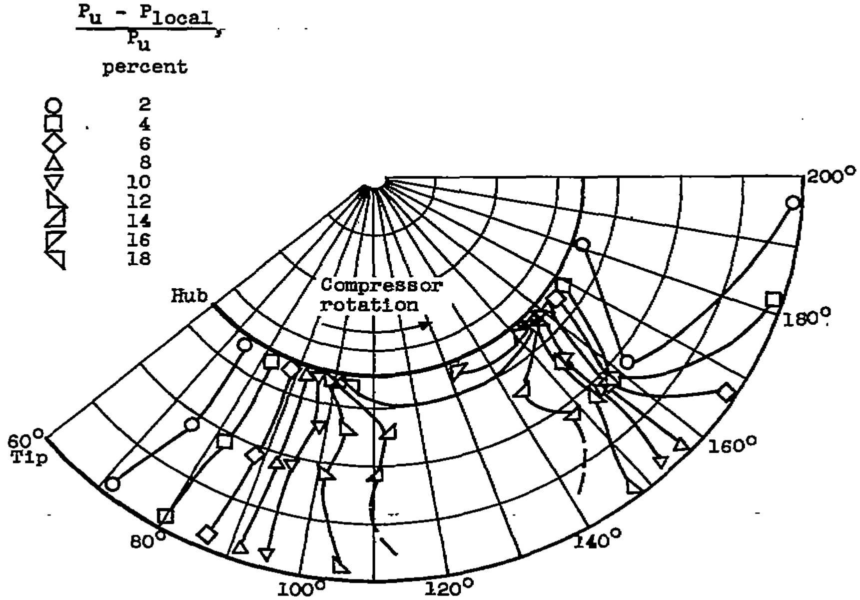
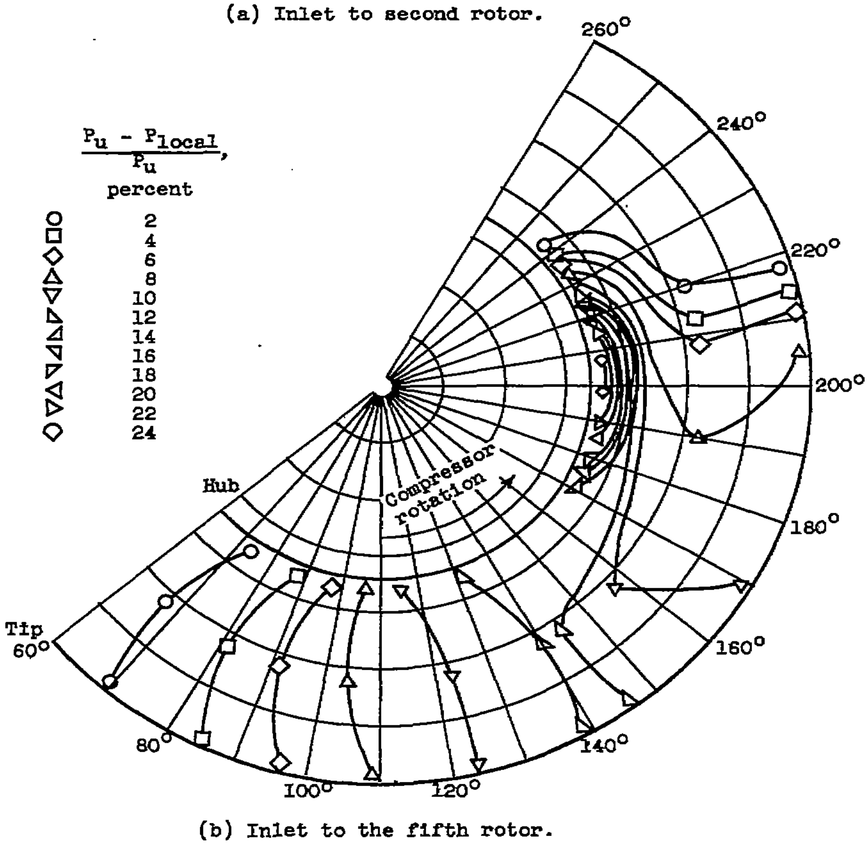


(a) Inlet to second rotor.



(b) Inlet to the fifth rotor.

Figure 10. - Total-pressure contours at several stages for a corrected engine speed of 6550 rpm. Distortion, 15 percent; 70° sector angle.

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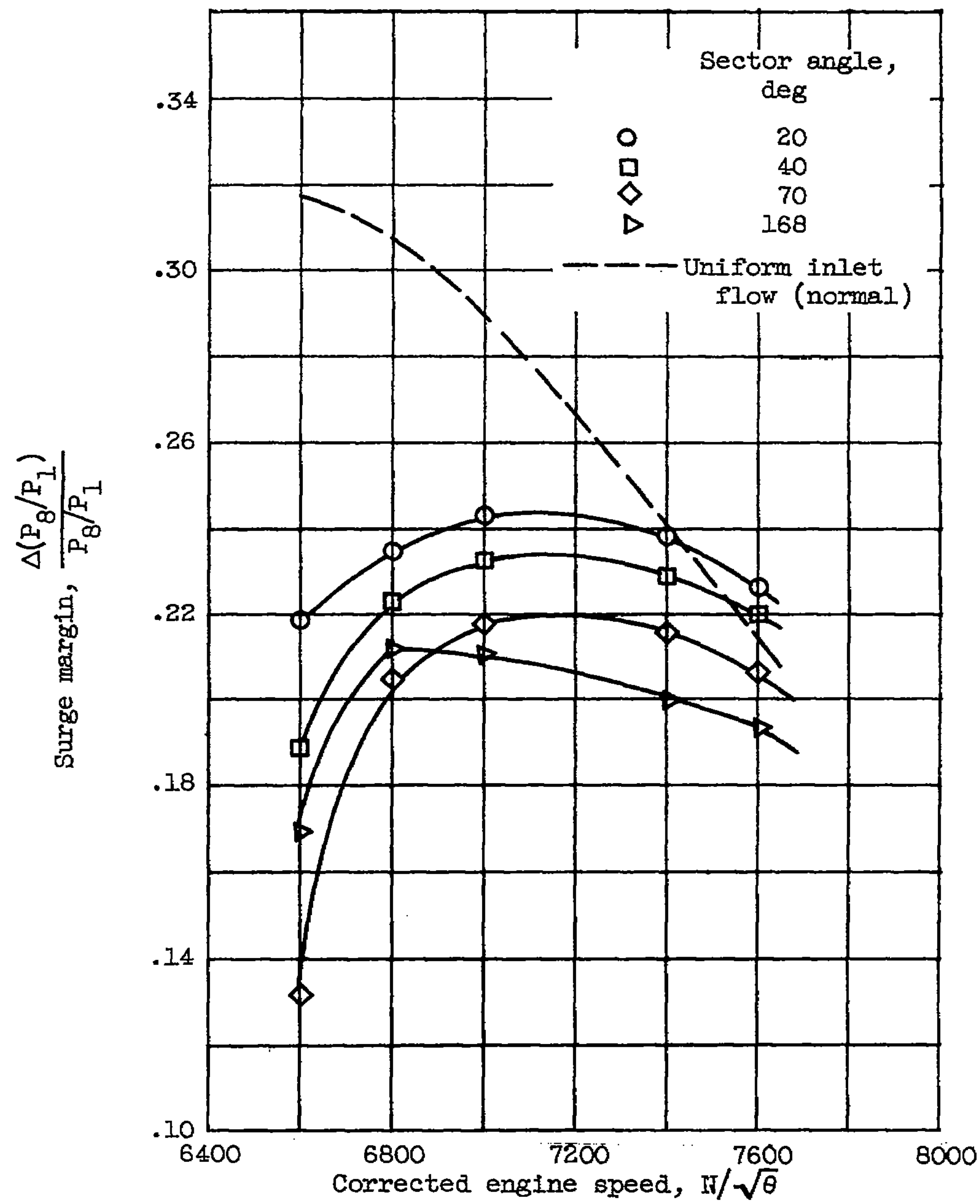

Figure 11. - Effect of distortion sector angle on surge margin. Distortion, 15 percent.

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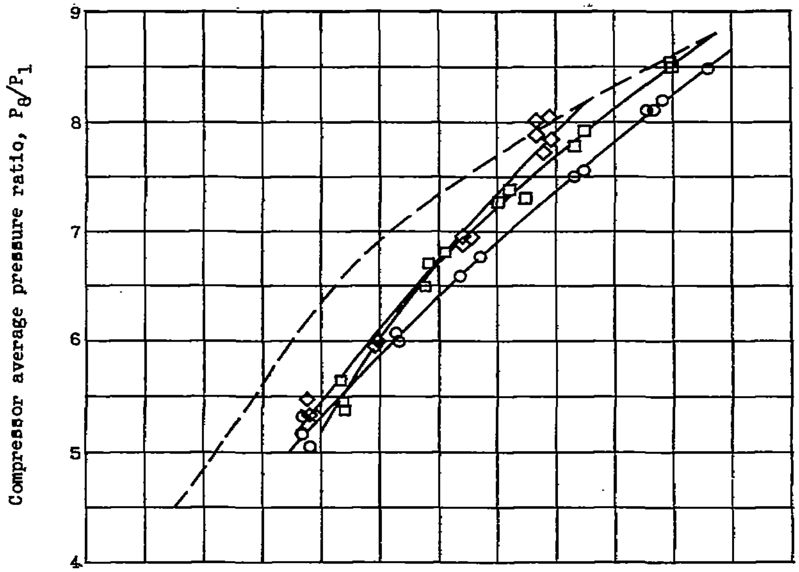
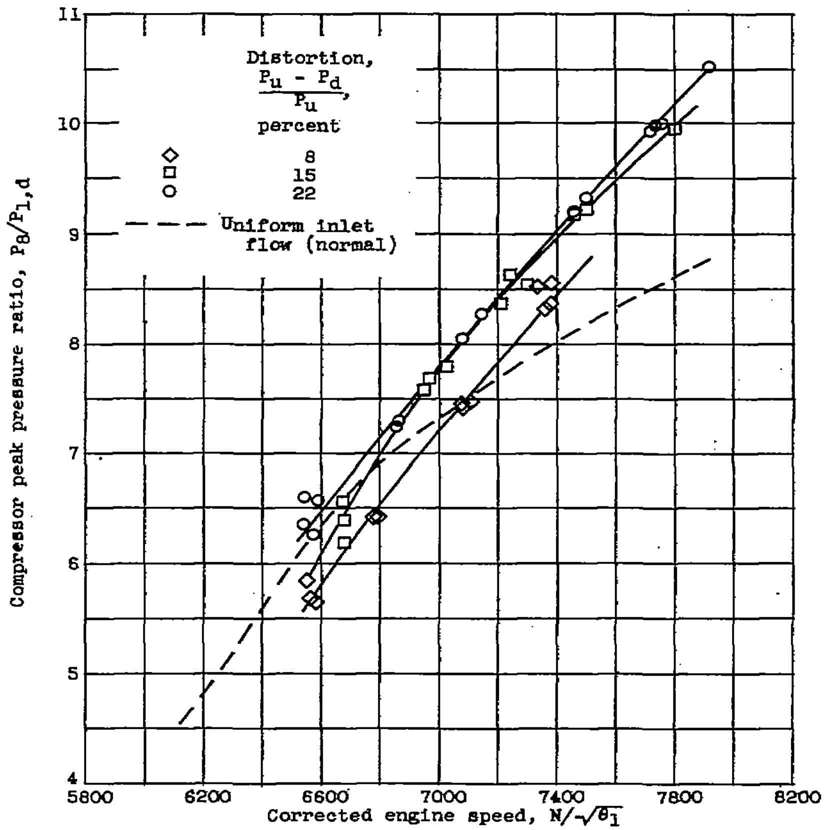


(a) Compressor average surge pressure ratio.



(b) Compressor peak surge pressure ratio.

Figure 12. - Comparison of compressor surge lines obtained with several percent distortions. Distortion sector angle, 70°.

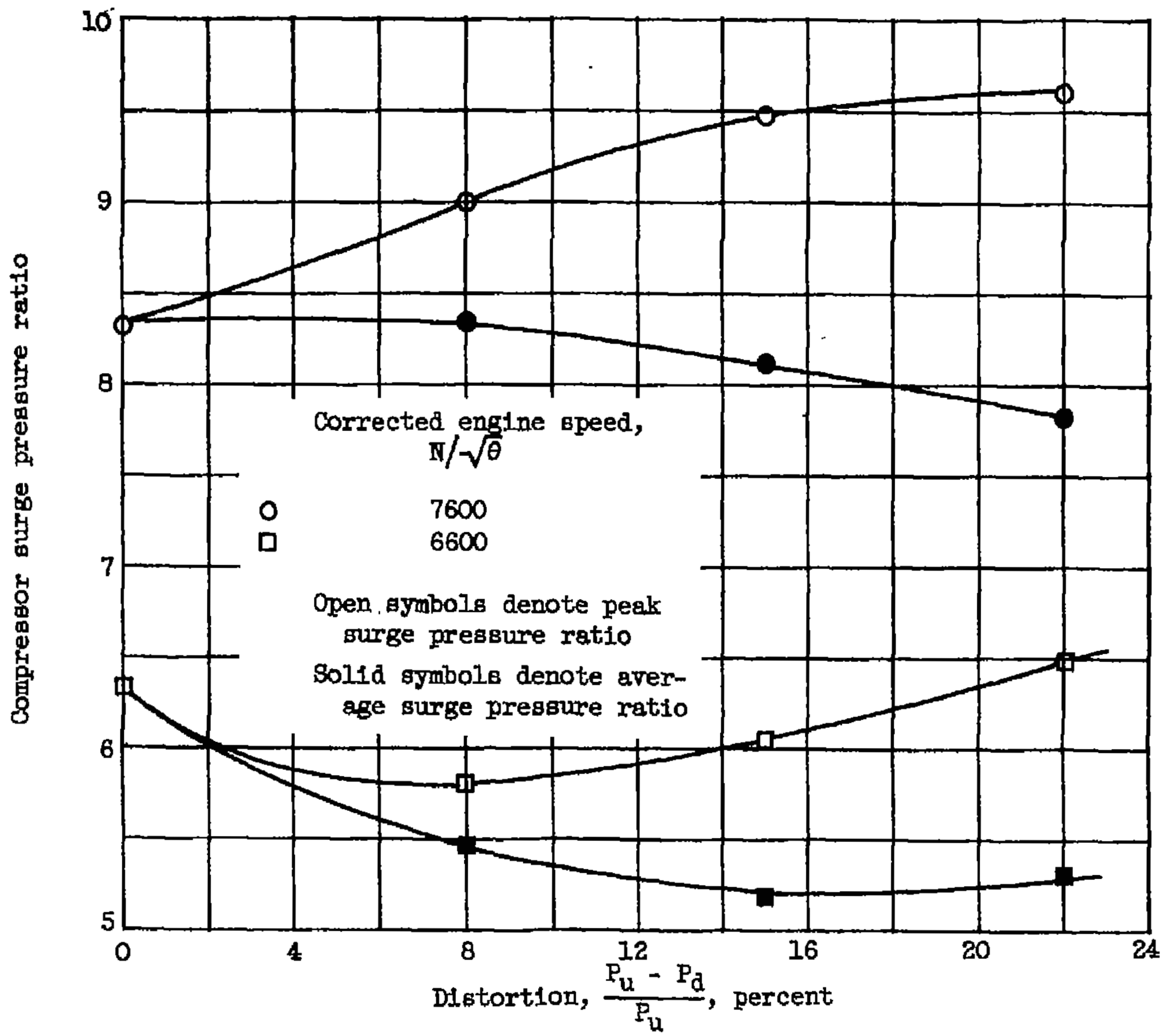


Figure 13. - Effect of percent distortion on compressor peak and average surge pressure ratio. Distortion sector angle, 70°.

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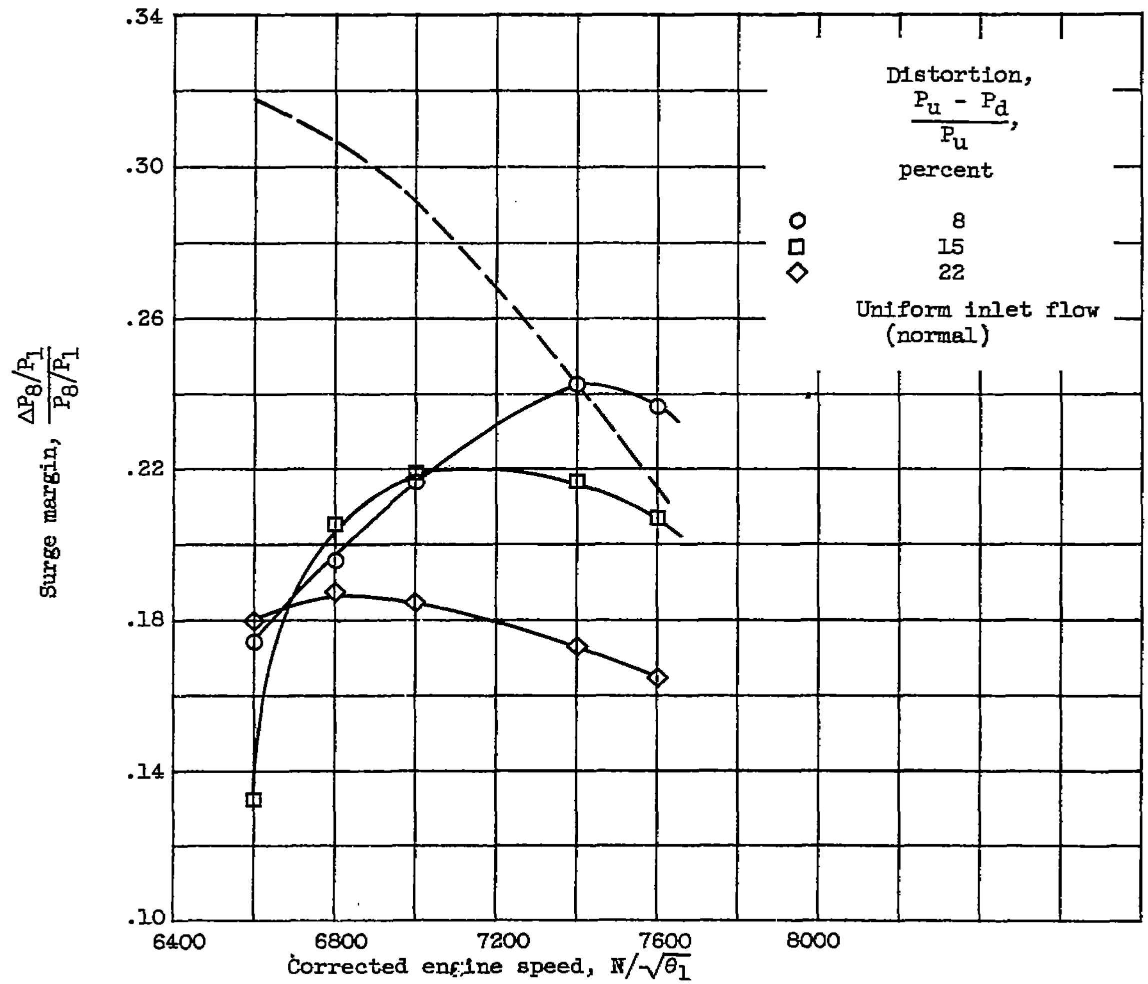

Figure 14. - Effect of percent distortion on surge margin. Distortion sector angle, 70°.

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